

THE AMERICAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

VOL. 13

JANUARY, 1928

No. 1

THE PLASTIC DEFORMATION OF ORE MINERALS

A PRELIMINARY INVESTIGATION: GALENA, SPHALERITE,
CHALCOPYRITE, PYRRHOTITE AND PYRITE

PART I

M. J. BUERGER, *Massachusetts Institute of Technology.*

ABSTRACT TO PART I

With a view of eventually using the data for the purpose of studying deformed ore mineral aggregates, the plastic characters of single crystals of several species have been investigated. The experimental method consists essentially of subjecting the single crystal to compression while embedded in a matrix which supplies a hydrostatic retaining pressure. Galena, whose plastic characteristics are, in several respects, simple, is first considered.

The positions of slip striations on deformed galena indicate that it deforms by translation along cube planes. The absence of striations on cleavage faces parallel with the load, when the latter is directed normal to a dodecahedral plane, gives the translation directions as $[110]$.

It is shown that deformation of galena involves a reorientation of crystallographic directions such that a $[111]$ direction tends to become parallel with the load.

The significance of the above phenomena is brought out in terms of atomic arrangement, and general principles are presented for the prediction of translation planes and directions in other simple lattices.

INTRODUCTION

In many ore deposits, of which those of Coeur d'Alene, Idaho, and adjoining districts of the same group are noteworthy examples, the ore minerals have suffered intense deformation resulting in the production of "sheared" galena, sphalerite and other minerals. Hand specimens from such localities often show ore with the textural aspects of gneisses or even schists. The galena shows, in detail, curved cleavage faces which, in polished sections, may be recognized by the contorted arrangement of the cleavage pits, especially where this soft mineral is in contact with a harder, more resistant material.

In deposits of this sort, the evidence of ore deformation is so clear that no reasonable doubt exists as to the sequence of events

which gave rise to the character of the present ores. The ore minerals were first deposited by filling and replacement—by just what mechanism is not of immediate concern—and subsequently were subjected to enormous compressive forces which distorted the original crystals. The evidence shows that the softer minerals were deformed through flowage, while often the harder ones, such as pyrite and quartz, were broken or crushed.

Besides this class of clearly deformed deposits, there exists a structurally related class whose origin is not so easily ascertained: deposits, especially of the pyrite-pyrrhotite-chalcopyrite type, whose ore bodies are arranged in lenses or tabular masses parallel, or nearly parallel, to the foliation of the obviously deformed country rock (usually a schist). On the basis of large-scale relations, the disposition of many such deposits can be accounted for by either of the two following hypotheses:

1. The ore was deposited, and later both ore and country rock were simultaneously deformed.

2. The country rock was first deformed, and subsequently, by a process of metasomatism, the ore replaced, preferentially, certain bands of the deformed rock, or was injected along its lines of foliation.

Field relations may yield evidence favoring one or the other of these possibilities, but often do not give all that is to be desired in the way of uncontrovertible criteria; they may appear to support equally well both views.

It seems desirable, therefore, to find evidence of another type and to develop criteria not immediately dependent on field relations. The study of individual crystals of the ore minerals and the consideration of the relations of one crystal to its neighbors, it is believed, will afford data which may be of value in determining how such a genetically doubtful ore-body has reached its present condition.

The problem of crystal criteria may obviously receive treatment in either of two ways:

1. By a study of the crystals from ore-bodies known on geological evidence to have been deformed simultaneously with the country rock.

2. By a study of crystals experimentally deformed.

Of these two methods of attack, the first is undesirable because it leads to rather empirical results. To make real progress in the

development and intelligent application of crystal criteria, a clear understanding of the nature of crystal deformation is necessary. The second, experimental, method of attack not only has the advantage of leading to a rational development of crystal criteria, but it should afford results which rest upon known grounds and are independent of geological reasoning. In addition, the conditions of experimentation may be varied within certain limits and controlled so that one variable at a time is changed.

It is primarily with the purpose of developing fundamentals, rather than presenting criteria that this paper is presented. Moreover, since a great number of ore deposits of the genetically doubtful type contain large proportions of pyrite, pyrrhotite, chalcopyrite, sphalerite and galena, attention will be particularly directed to such of these minerals as can be conveniently treated in an experimental way.

Probably because of its more immediate economic significance, the greatest amount of recent experimental work on crystal deformation has been conducted on metal crystals.¹ In the realm of mineral crystals, Adams,² Adams and Coker,³ Veit,⁴ and others have investigated plastic flow, but without special consideration to the mechanism of the attendant reorientation phenomena. The writer will give these processes some consideration in the following discussion since it is preliminary to a later development of criteria for the recognition of deformed ores.

¹ See, among others, the following papers: M. Polanyi, Deformation von Einkristallen: *Zeit. Krist.*, **61**, pp. 49-57 (1924-25). K. Weissenberg, Zur Systematik und Theorie der Wachstums und Deformationsstrukturen, *idem*, **61**, pp. 58-74 (1925-26). H. Mark, Über die Methode und die Ergebnisse der experimentellen Bestimmung von Wachstums und Deformationsstrukturen, *idem*, **61**, pp. 75-91, (1924-25). Orlando E. Romig, Preparation of Metallic Single Crystals and Twinning in Zinc and Zinc Single Crystals, *Proc., Institute of Metals Division, Am. Inst. Min. Met. Engs.*, pp. 90-112, (1927). Samuel L. Hoyt, Plastic Deformation of a Zinc Single Crystal, *idem*, pp. 116-132, (1927). C. H. Mathewson and Albert J. Phillips, Plastic Deformation of Coarse grained Zinc, *idem*, pp. 143-189, (1927). J. T. Norton and B. E. Warren, Plastic Deformation of Metals, *idem*, pp. 350-366, (1927).

² Frank D. Adams, An Experimental Investigation into the Action of Differential Pressure on Certain Minerals and Rocks, Employing the Process Suggested by Professor Kick, *Jour. Geology*, **18**, pp. 489-525 (1910).

³ Frank D. Adams and Ernest G. Coker, An Experimental Investigation into the Flow of Rocks, *Am. Jour. Sci.*, (4) **29**, pp. 465-487 (1910).

⁴ Kurt Veit, Künstliche Schiebungen und Translationen in Mineralien, *Neues Jahrb. f. Min. Geol. u. Pal.*, Bl. Bd. **45**, pp. 121-148 (1922).

THE EXPERIMENTAL METHOD

Many crystals, such as those of the very pure, ductile metals, can be made to suffer great deformation without the development of cleavage, parting, or irregular cracks. This is probably due to the unique properties of free electrons in the lattice. Frangible crystals, relatively low in, or entirely lacking these electrons, may also be made to flow provided an external pressure, in a certain sense replacing these electrons, is applied. In nature, otherwise brittle minerals have flowed readily when aided by the lateral support which the retaining force of the surrounding crystals afforded.

Lateral support can be provided experimentally by an ingenious method devised by Kick,⁵ which has been used with great success on the softer minerals by Adams⁶ and others. In brief, the method consists of embedding the crystal in a matrix, which can later be removed by fusion or solution, within a tube of ductile metal. The ends of the tube are capped by means of brass plates and the whole subjected to a load applied parallel to the axis of the tube. The initial application of load causes the tube to sink somewhat into the end plates, effectively sealing the arrangement against any escape of embedding material. Further load compresses the matrix and this continues until the hydrostatic pressure combined with the axial load on the tube causes the latter to bulge equatorially. When this occurs the matrix and crystal are enabled to flow laterally restrained by the centripetal pressure exerted by the bulging tube. Since an initial force of a certain finite amount is required before the matrix undergoes plastic flow the crystal is subjected to a differential pressure which is essentially equivalent to a hydrostatic retaining pressure upon which is superimposed a direct load.

Adams used tubes of copper and employed for embedding medium: paraffine wax, fusible metal, sulphur, and alum in various experiments. He found alum to give the best results due to its greater resistance to flow.

In the experiments to be described on the following pages Kick's method was used because of its cheapness and convenience

⁵ Friedrich Kick, *Die Prinzipien der mechanischen Technologie und die Festigkeitslehre, Zeit. des Ver. Deut. Ingen.*, 36, pp. 919-923, (1892).

⁶ *Op. cit.*

and the writer has followed Adams closely, partly with the hope that the results might prove, in a rough manner, comparable, and partly to avoid useless experimentation. Copper tubes of the same dimensions, except length, as those described by Adams were utilized. These were of commercial stock known as one-inch iron pipe size; although irregularities occurred these had the following average dimensions:

Internal diameter 1.063 inches.

External diameter 1.125 inches.

Brass plates one-tenth of an inch thick and two inches square were used for end pieces, and these were in turn capped by wrought iron blocks one-half inch thick and two inches square.

In all cases, except in two unsuccessful experiments with paraffine, U. S. P. potassium aluminum alum was used as an embedding medium. This was melted and a little poured into the copper tube. The crystal then could be supported by forceps and partially immersed in the molten alum until the latter congealed. When this occurred, the remaining space was filled with alum and the tube and its contents set aside to cool. After solidification, that portion of the alum projecting beyond the tube was cut off and filed to make a flat surface flush with the end of the tube.

An axial load was applied by submitting the tube and its contents, capped by brass and iron end plates, to compression in a long-column Olsen testing machine having a capacity of 100,000 pounds. Except with the last chalcopyrite crystal deformed, the load was applied at a rate of .03 inches per minute.

Usually the applied load mounted rapidly in the beginning of each test. As soon as the tube and its contents started deforming in a plastic way (as noted by the incipient equatorial bulge of the tube) the load remained constant for some minutes, and later increased slowly.

In comparing maximum loads, one should remember that too great weight does not attach to these values. As pointed out by Adams,⁷ it is impossible to calculate accurately the stresses set up in the enclosed specimen; so many variables are involved (size of specimen, length of tube, variability of alum due to melting processes, etc.) that the values themselves are only the roughest sort of a measure of the force used to deform the particular specimen.

⁷ *Op. cit.*, p. 495.

EXPERIMENTS ON SINGLE CRYSTALS OF CERTAIN SPECIES AND
THE LATTICE SIGNIFICANCE OF THE RESULTS

A. GALENA

PREVIOUS WORK.—The original literature on the deformation of galena is largely hidden in old and unavailable publications, but a good summary is given by Hintze.⁸

Weiss⁹ described the galena percussion figure consisting of one or more cracks parallel to cube edges, developed by means of a sharp blow on a steel needle in contact with a cleavage face. More interesting is the pressure figure.¹⁰ Pressure applied to a cleavage face by means of a rounded point produces a pyramidal hole whose sides are parallel to cube-face diagonals. A corresponding pyramidal hill is simultaneously developed on the under side of the cleavage flake. Bauer interpreted these phenomena as a gliding on dodecahedral planes.

Mügge¹¹ noticed that galena crystals from Rhodna which were bent about an axis parallel to a cube-face diagonal, were covered with fine striae parallel to cube edges, which intersected in such a manner as to preclude the possibility of their being growth lines. Mügge explained these as traces of gliding planes which had sustained translation in the direction of the cube-face diagonal. He confirmed these conclusions by several experiments. In one he placed a cleavage cube of galena upon one side of a shallow V-shaped groove in such a manner that a cube-face diagonal was parallel to the dip of this side of the groove. Then by pushing upon the uppermost corner of the galena cube he was able to deform it into a blunt parallelepiped. Four sides of the galena block (in one zone) were found to be covered with translation striae parallel to the other two cube faces.¹² In another experiment he supported two adjacent corners of a cleavage cube, leaving the rest of the edge joining these corners unsupported. By pressing the middle of the opposite edge, he was able to (ap-

⁸ Carl Hintze, *Handbuch der Mineralogie*, Erster Band, *Lfg. 1*, Leipzig, pp. 461-464 (1898). Also O. Lehmann, *Flüssige Kristalle*, p. 106, Leipzig (1904).

⁹ Weiss, *Zeit. der deutschen geol. Gesell.*, 29, pp. 208-211 (1877).

¹⁰ Max Bauer, *Beiträge zur Mineralogie*: 5, Über des Vorkommen von Gleitflächen am Bleiglanz, *Neues Jahrbuch für Min. Geol. u. Pal.*, I, pp. 138-150 (1882).

¹¹ O. Mügge, Über Translationen und verwandte Erscheinungen in Krystallen, *Neues Jahrbuch für Min. Geol. u. Pal.*, I, pp. 123-138 (1898).

¹² See Mügge's figures 32 and 33, *Op. cit.*, p. 126.

parently) bend the crystal, with the production of translation striae parallel to the end cube faces. Mügge thus concluded that galena deforms by translation on $\{100\}$ planes in $[110]$ directions. Critically analyzing the percussion figure of Weiss and the pressure figure of Bauer, he re-explained these as translation on $\{100\}$ combined with bending.

Cross¹³ has described galena from Bellevue, Idaho, with striations parallel to (110) and explains this as due to translation along dodecahedral planes as in the case of Bauer's experiments. He also notes indications of twinning on (331) and (111) . These effects, he concludes, are secondary and to be ascribed to pressure.

The writer repeated Mügge's experiments with essentially the same results and conclusions. In order to ascertain whether the same results would be expected under natural conditions, in which the pressure is not directed in any particular manner, but is completely at random with respect to crystal orientation, and in which, in addition, it has superimposed upon it a hydrostatic pressure, he carried out the following investigation.

EXPERIMENTS.—Several experiments were tried on galena with a load normal to an octahedral plane. In the first a crystal from Dubuque, Iowa, was used. This showed the octahedron predominating with rather small cube-faces modifying octahedral corners. The faces were not equally developed but were essentially free from any notable curvature. The surfaces were dull and contained many small irregularities, some of which were presumably etch pits. In order, therefore, to facilitate observation of any slip to be produced in deformation, several of the faces were polished.

The specimen was embedded in alum within a copper tube .9 inches high, and oriented so that the load was normal to an octahedral face. This orientation is reproduced in Fig. 1-A. When so orientated the crystal was .50 inches high. After applying a load of 37,700 pounds the crystal was removed by solution of the alum and found to have been reduced in height to .41 inches (See Fig. 2-A). The specimen displayed only the slightest traces of cracking and true cleavage and was very coherent. All originally plane-polished faces were curved. Obviously galena deforms in a plastic way with relatively great ease.

¹³ Whitman Cross, *Proc. Colorado Sci. Soc.*, 2, pt. 3, p. 171 (1885).

Microscopic observation showed that the polished faces were minutely striated parallel to cubo-octahedral edges as shown in Fig. 3.

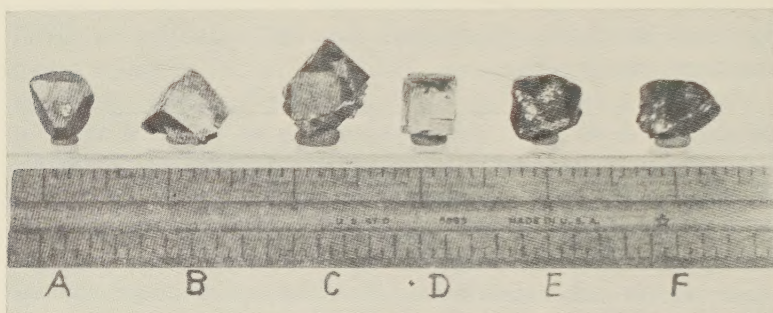


Fig. 1. Photograph of six of the single crystals used in the deformation experiments. Except in the case of C, these specimens are oriented as they were within the copper tube, the loads being applied in a vertical direction. It was intended to deform C when oriented as shown, but the crystal was dropped during the embedding process and the load was applied at an angle of 45° to the plane of the paper.

A, B, C, and D..... galena
 E..... sphalerite
 F..... chalcopyrite

The scale shown is in inches.

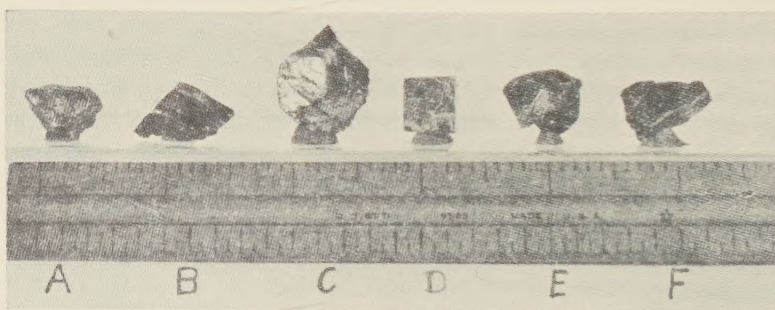


Fig. 2. Photograph of the same six crystals shown in Fig. 1 but after deformation. Note the flattening of A and B normal to a vertical direction and of C in a direction oblique to the plane of the paper. Note also the bending of F. Notation and scale are the same as in Figure 1.

To check these observations, other experiments were made. A slightly curved cubic crystal from Joplin was obtained. It was incomplete, having one ragged surface by which it had evidently

been attached. As in the case of the preceding specimen, the faces were polished before deformation.

The specimen was embedded in alum in a .9 inch copper tube and oriented so that a load could be applied normal to an octahedral plane. The original height was .60 inches (See Fig. 1-B). After applying the load of 36,000 pounds its height had been decreased to .54 inches (See Fig. 2-B). The previously polished faces had become quite curved and were coarsely striated due to the gouging action of the alum. Although a number of cleavage cracks had developed, the crystal was very coherent and showed no tendency to break on repeated dropping.

Detailed observation with binoculars and metallographic microscope showed that, in addition to the coarse alum grooves, the curved cube faces were covered with fine lines parallel to the cube edges (Fig. 4). Along the grooves produced by the alum sliding over the galena (where deformation must have been highly localized and very intense) these lines were especially abundant. The spacings of these lines were highly variable; the smallest spacing between striae actually measured was approximately .001 millimeters. Other spacings were as large as .01 millimeters, or more. Where lines of wide separation were noted under the binocular, the metallographic microscope showed still finer lines between these.

A third experiment was conducted in a manner similar to the above with identical results.

All the observed slip band traces are in harmony with a translation occurring on cube planes. Several experiments were next conducted to check this hypothesis.

If slip occurs on cube planes, a load directed normal to one cube plane and therefore parallel to two others should have no components in these planes and consequently no translation is to be expected under these conditions. The validity of the inference as to the location of the planes of easiest slip was accordingly put to a test by attempting to deform in the usual way a cleavage cube with a load of 33,800 pounds applied normal to a cube face. No measurable deformation was attained and no slip striae appeared (compare Figs. 1-D and 2-D). Two other cleavage cubes were similarly loaded to 51,000 and 57,000 pounds, respectively, without measurable deformation or production of slip lines. In these cases, however, the harder alum crystals

impressed themselves on the bases of the test pieces with a formation of hills and depressions similar to those seen in pressure figures. Finally, a fourth cleavage cube was mounted so that the pressure could be applied almost, but not quite, normal to a cube face. A load of the same magnitude as the preceding brought about an appreciable deformation and covered the cube with translation striae parallel to cube edges.



Fig. 3. Diagrammatic representation of striation directions on the first galena crystal deformed, with the load normal to an octahedral plane.

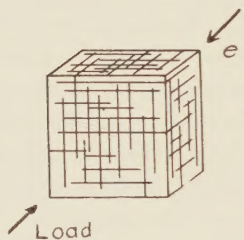


FIG. 4. Diagrammatic representation of striation directions on the second galena crystal deformed with a load normal to an octahedral plane

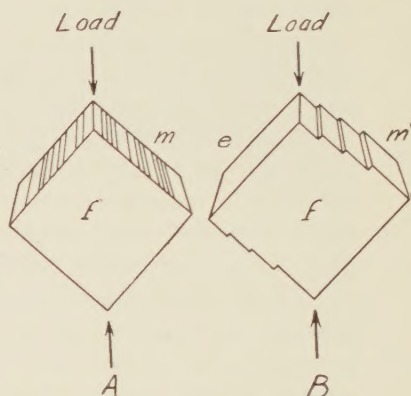


FIG. 5. Striations resulting from slip on cube planes if the cube edge, [100], is the translation direction. A shows the actual cube. B is a diagrammatic representation of striation production if only one set of cube planes, *e*, slip. Actually both sets, *e*, and *m*, slip and produce striations on faces *m* and *e* as shown in A. Note that no striations appear on face *f*.

These experiments seem to indicate that under moderate load galena will deform by translation on $\{100\}$ planes. The structural significance of this will be brought out on another page.

It is of importance to know not only the translation plane but also the translation direction in galena. Mügge deduced [110] as the translation direction from the fact that deformed galena crystals were apparently bent about a cube-face diagonal. It is desirable to have additional evidence on this point since this deduction rests, in a measure, on the "Biegegleitung" hypothesis.

Since the cube edge and cube-face diagonal are the only first order directions in the cube plane, slip must, from theoretical considerations, occur in one of these directions. If the cube edge is the translation direction, then a load applied to a cleavage cube normal to a dodecahedral plane should produce no striations on the cube face parallel with the load direction. This is shown diagrammatically in Figs. 5-A and 5-B. If, on the other hand, the cube-face diagonal is the translation direction, striations should appear on these faces, as shown in Figs. 6-A and 6-B.

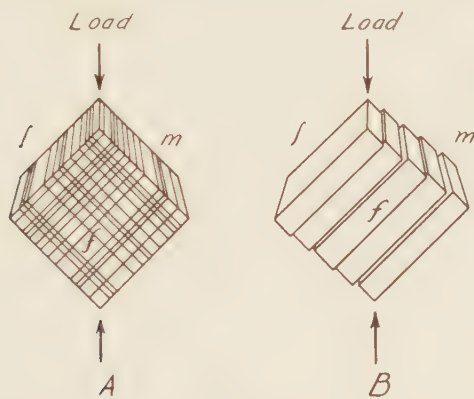


FIG. 6

Striations resulting from slip on cube planes in the direction of cube face diagonals, $[110]$. A shows the actual cube. B is a diagrammatic representation of striation production if only one set of cube planes, l , slip. Actually both sets, l and m , would slip and produce striations on faces m and l as shown in A. Note that in this case striations appear also on face f .

Several polished cleavage cubes were deformed with a load normal to a dodecahedral plane and in each case the striations observed were those shown in Fig. 6, proving that $[110]$ is the translation direction. Our results are, therefore, in agreement with Mügge's conclusions.

REORIENTATION PHENOMENA.—Figure 7 shows diagrammatically that slip along a single plane results in a reorientation of crystal directions, the plane of slip tending to assume a position nearer normal to the direction of the applied load. When slip occurs on two planes at once, the reorientation processes are more complicated. The shearing component (which is responsible for slip) is

greatest in directions making angles of 45° with the direction of the force and zero parallel with and perpendicular to it. Hence if slip occurs simultaneously in two directions not at right angles. to one another it will occur most easily and therefore most rapidly in that direction which makes an angle nearest 45° with the load. This tends to rotate the entire crystal so that the more rapidly slipping plane makes an angle with the initiating force which is less favorable to slip, and so that the less rapidly slipping plane makes an angle with the force which is more favorable to slip.

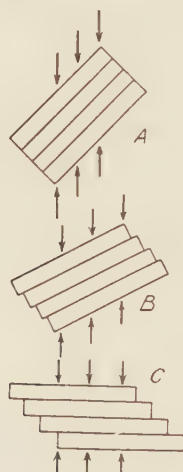


FIG. 7

Diagrammatic representation of the reorientation process of a crystal having only a single family of possible translation planes. Arrows indicate system of loading.

Eventually a condition of equilibrium is approached in which slip takes place as easily on one plane as on the other. This occurs when the direction of the force bisects the angle between the directions of slip as has been shown by Norton and Warren.¹⁴

When, as in the case of galena, slip occurs in three different directions (cube-face diagonals in galena) the mechanism is a little more difficult to visualize. In the general case, however, the same reasoning applies. Translation in the direction most favorably located for slip tends to rotate the whole crystal so that that

¹⁴ J. T. Norton and B. E. Warren, Plastic Deformation of Metals, *Proc., Institute of Metals Division, Am. Inst. Min. Met. Engs.*, p. 353 (1927).

direction assumes a less favorable position while the other two directions are rotated into more favorable positions. A condition of equilibrium is approached on long-continued deformation in which all slip directions make equal angles with the deforming force.

A crystal of galena of random original orientation, then, should be expected, after sufficient deformation, to be so oriented that the deforming force makes equal angles with three cube-face diagonals. In such an orientation the crystal will have the cube diagonal, $[111]$, parallel with the force.

In addition to this random original orientation two special orientations must be considered:

(1) If the original orientation with respect to the load is such that two cube planes make random angles with the direction of the force and the third is parallel with the load, there is no component of slip in the latter plane. Slip may occur in $[110]$ directions on both cube planes which are not normal to the load, however, and the crystal approaches an equilibrium position such that the load bisects the dihedral angles between these two planes, that is, the load becomes parallel to a dodecahedral direction.

(2) The experiments show that easy deformation occurs only when the cube face is not approximately normal to the applied load. When it is nearly normal, slip along cube planes is so difficult and slow that the previously mentioned reorientation can not be expected to take place. While the experiments are incomplete on this point, speculations detailed on another page compel belief that a galena crystal so oriented will deform by slipping on dodecahedral planes along $[110]$ directions. In this case there are four directions of simultaneous slip and since these all make initially equal angles with the deforming force the crystal is in an equilibrium position and retains its original orientation.

Since a single crystal of random original orientation, when subjected to deforming forces, tends to assume the equilibrium position with an octahedral direction aligned parallel to the load, it might be supposed that a deformed galena aggregate could be recognized (as having been deformed) by the shape of the cleavage pits on a surface polished normal to the load direction; the pits would be expected to be all equilateral triangles in outline on such a surface. The reorientation phenomena are not so simply applied, however, since, in deformed ore-crystal aggregates several

complicating features¹⁵ are present. A casual examination of moderately deformed ore will show that on surfaces polished normal to the presumed load direction, the galena cleavage pits, although curved, do not display the expected uniformity of character, *i. e.*, all pits are not equilateral triangles in outline, nor do they more than remotely approach this condition.

For the practical recognition of reorientation and its deformation significance in aggregates, recourse must be had to the more delicate and statistical X-ray method employed so successfully by Mark¹⁶ and Warren and Norton¹⁷ on the metals.

STRUCTURAL CONSIDERATIONS.—X-ray analysis has shown that a true crystal is built up of an orderly array of atoms (more strictly ions) arranged in a regular manner on points of an imaginary space-lattice.¹⁸ The concept is too well known to require

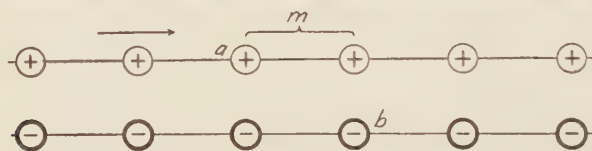


FIG. 8

A possible translation direction (Galena: two (001) planes seen looking in a [110] direction). Translation of the upper plane past the lower one for a distance m will bring positively charged ion, a , to a position above negatively charged ion b . This final disposition of charges is identical with the original and no inherently unstable configuration is approached during movement.

exposition here. In the simpler crystalline compounds, at least, the atomic volume requirements practically necessitate, according to Foote,¹⁹ a figurative squeezing off of valence electrons from those atoms in the structure having chemically positive tendencies, and acquisition of these squeezed off electrons by those atoms having chemically negative tendencies. The net result is a structure of positively and negatively charged ions.

Plastic deformation has been observed to occur by two processes: translation and twinning. Translation involves a slipping movement between adjoining portions of the crystal along certain

¹⁵ To be discussed in a later paper on criteria.

¹⁶ *Op. cit.*

¹⁷ *Op. cit.*

¹⁸ Ralph W. G. Wyckoff, *The Structure of Crystals*, New York (1924).

¹⁹ Paul D. Foote, *The Relation between Metallurgy and Atomic Structure*, *Trans., Am. Inst. Min. Met. Engs.*, **73**, p. 647 (1926).

planes in such a manner that the crystalline bands are not destroyed during the process but merely shifted, or handed on along the slipping planes. The bands are conceivably of three kinds: the electrostatic attraction between ions due to their unlike charges, the gravitational attraction between ions due to their masses, and the magnetic attraction between ions due to their magnetic fields. Any two adjacent planes in a crystal may be conceived of as cohering to one another by reason of these three sets of forces, although the first greatly predominates; the electrostatic attraction is the conditioning cohesive one.

The planes will continue to remain in cohesive contact during translation provided that the displacement between planes takes place in a direction such that the mutual relation of charged atoms

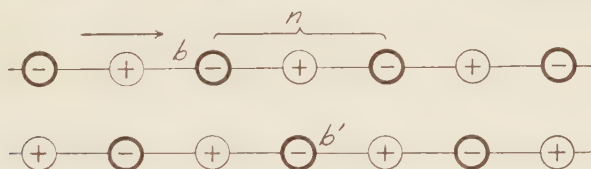


FIG. 9

An impossible translation direction (Galena: two (001) planes seen looking in a [100] direction). An attempt to slide the upper plane past the lower one for a distance, n , would give a disposition of charges identical with the original, but such a movement would necessitate having negatively charged ion b above negatively charged ion b' at some time during the process. Such a configuration is unstable due to the enormous repulsive forces between like charges and a directed attempt to initiate translation in the direction indicated would result in instant cleavage between the two planes.

(ions) in one plane, with respect to those in the other, is the same in the final configuration as it was originally; and provided further that no inherently unstable configuration between planes is approached during the process. Figures 8 and 9 will serve to illustrate this point. If, in Figure 8, translation of the upper plane past the lower one for a distance m (or any multiple thereof) is caused to take place in the direction of the arrow, positively charged ion, a , is moved to a position above negatively charged ion, b . This final disposition of charges is identical with the original, and no inherently unstable configuration is approached during movement. On the other hand, with the translation direction as shown in Figure 9, it will be noted that while the final position would be identical with the original (in the sense of charge distribution) if the upper

plane is displaced a distance, n , in the direction of the arrow, the movement would require the like charged ions of adjacent planes to approach closely one another at some time during the displacement (b would be above b' , for example). Should an attempt be successful in initiating translation in the direction indicated, therefore, instant cleavage would result due to the enormous repulsive forces between like charges in adjoining planes.

These considerations may be summarized in the following principle: Translation may occur only in those crystallographic directions which are parallel to rows of consecutively like charged ions in the lattice. Although the *direction* of translation is thus completely fixed for a given crystal structure by the disposition of charged ions, the kind of *planes* between which actual displacement can occur may vary with the conditions of loading. For a crystal of random orientation with respect to the direction of loading, the translation plane can be predicted from the following considerations:

While any plane containing a translation direction is at least a potentially possible translation plane (merely because it contains the translation direction), translation will occur along that one presenting the least resistance to slip. The slip resistance is due to,

(1) The restoring forces arising from displacing elastically the ions of adjacent planes against their mutual electrostatic, gravitational, and magnetic attractions.

(2) Interatomic friction, resulting presumably from an interpenetration and disturbance of atomic spheres of influence during movement.

For two isolated ions, the three factors of (1) vary inversely as the square of the distance between ions. Certainly the integrated effect of all ions in retarding slip along a given pair of planes, both for reasons (1) and (2), will decrease rapidly with the spacing of the planes. Therefore, translation will be highly favored along the planes of greatest spacing. Should the direction of application of the load be normal or parallel to all such planes of greatest spacing, slip will be favored along those planes of next greatest spacing.

To summarize these translation conditions: Translation will occur along that family of planes containing a translation direction, which has the greatest interplanar spacing. It can be seen that the translation direction, although difficult to obtain experimentally,

is of greater *fundamental* importance than the translation plane, which is easily determined by observation of slip striations.

To intelligently apply the translation conditions to a given crystal, a lattice model must be constructed since a two-dimensional representation of the lattice gives only a difficultly grasped conception of atomic planes and lines. Galena utilizes the sodium chloride arrangement in crystallizing, and a single unit cell of this structure is shown in Figure 10. By examining a large model consisting of many unit cells, it is at once apparent that there are six directions in which atoms of like charges are

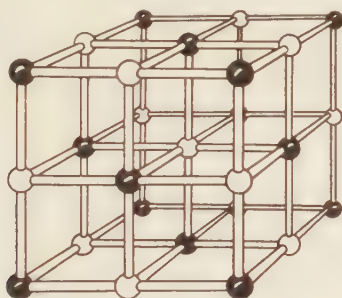


FIG. 10

Unit cell of galena. Either black or white balls may be taken to represent centers of lead or sulphur atoms.

consecutively arranged. These are the directions normal to the six dodecahedral planes, *i. e.*, $[110]$ directions. The model shows at once that the planes of greatest spacing are the cube planes. Dodecahedral planes have the next greatest spacing and octahedral planes have the least spacing of the first order planes. Hence, a galena crystal in random orientation would be expected to deform by slip along cube planes in $[110]$ directions. This is in complete harmony with the experimental evidence previously detailed.

(To be continued)

MIARGYRITE AND TETRAHEDRITE FROM THE
FLINT DISTRICT, IDAHOEARL V. SHANNON,¹ *U. S. National Museum.*

The silver-antimony sulphide, miargyrite, has the formula $\text{Ag}_2\text{S} \cdot \text{Sb}_2\text{S}_3$ and is monoclinic in crystallization. It commonly has a red streak and, in silver ores, is confused with pyrargyrite ($3 \text{Ag}_2\text{S} \cdot \text{Sb}_2\text{S}_3$), the common antimonial or dark red ruby silver ore. Although it was known from several European silver mines as well as from localities in South America and Mexico, until recently the only reported locality in the United States for this mineral was the Henrietta mine in the Silver City District, Owyhee County, Idaho. A specimen in the University of California collection was labeled as having come from the Rising Star Mine, in the Flint district.² Although Penfield described the mineral from the Henrietta mine, no description of the material from the Flint district has appeared. The present short paper is intended to furnish a description of certain specimens from this locality which were received in March 1925, by the U. S. National Museum from Mr. Victor C. Heikes which contain miargyrite crystals of unusually large size (U.S.N.M. Cat. No. 95143) and two additional specimens received a little later from Dr. W. W. Jones of Jordan Valley, Oregon (Cat. 86571).

The specimens, which are evidently from the center of an open vein, consist of coarsely crystalline quartz which forms loosely aggregated terminated prismatic crystals up to 5 cm. long and 2 cm. thick. These contain a small proportion of metallic minerals, but chiefly sphalerite and miargyrite. The quartz and miargyrite are approximately contemporaneous in age, and large miargyrite crystals, deposited in interstices between crystals of quartz, are partially concealed by continued growths of quartz crystals.

The sphalerite forms honey yellow to rich golden brown crystal grains averaging 3 mm. in diameter. These are a little older than the first generation of miargyrite crystals.

The miargyrite crystals reach a length of 2 cm. with a breadth of 1 cm. They are partly concealed by the overgrown quartz crys-

¹ Published by permission of the acting Secretary of the Smithsonian Institution.

² Minerals of Idaho. *U. S. Nat. Museum, Bull.* 131, pp. 144-150.

tals. There were none of these suitable for goniometric measurement. They are elongated along the b axis and show the usual habits with prominently striated and rounded faces of two zones— $(100) \wedge (001)$ and $(100) \wedge (111)$ as is usual for the mineral. In color it is iron black with a reddish tinge but assumes a bluish or bronze tarnish on exposure. It is soft with vitreous metallic lustre, conchoidal fracture and dark red streak. Mr. M. N. Short of the U. S. Geological Survey has examined the material metallographically and very kindly furnished the following properties for it.

Color:	Gray with red internal reflections in places.
Anisotropism:	Strong.
Color in powder:	Dark ruby red—distinctly darker than pyrrargyrite.
1:1 HNO ₃ :	Negative.
1:1 HCl:	Fumes tarnish; in places negative.
20% KCN:	Slowly stains brown.
20% FeCl ₃ :	Negative.
40% KOH:	Stains iridescent.
5% HgCl ₂ :	Negative.

The sections of miargyrite were found homogeneous, pure and free from intergrowth with other minerals.

Where not covered by the later quartz the miargyrite crystals are spangled with brilliant, equidimensional, small iron black or iridescent metallic crystals which at first were thought to be a second generation of miargyrite but which were later found to be tetrahedrite. These little crystals average hardly 0.25 mm. in diameter and are oriented at all angles with reference to each other and to the miargyrite on which they rest. These crystals, somewhat highly modified, were placed on the goniometer and measured. They show faces of the tetrahedron p (111), the hemi-tetragonal trisoctahedron q (112) and the rhombic dodecahedron d (110). The habit is as shown in figure 1. In the clinographic projection the faces have been lined and stippled in an endeavor to show the characteristics which mark the faces of the several forms. These are of greatest value in orienting crystals of tetrahedrite, the symmetry of which is at times not apparent. The faces of p (111) are smooth and brilliant. The faces of q (112), although brilliant, are striated parallel to the edges $q \wedge d$ and the faces of d (110) are etched to dullness and have a bronzy sheen. The angles measured on crystals of the type figured identify the forms as follows:

MEASUREMENTS OF TETRAHEDRITE

FORM		SYMBOL Miller	QUALITY		MEASURED		CALCULATED	
No	Letter		Gdt.	Description	φ	ρ	φ	ρ
1	<i>d</i>	(011)	01	Very dim, etched	1°49'	46°22'	0°00'	45°00'
		(110)	∞	" " "	45°51'	90°53'	45°00'	90°00'
2	<i>q</i>	(112)	$\frac{1}{2}$	Striated, multiple	44°26'	35°15'	" "	35°16'
		(121)	12	" "	26°50'	68°55'	26°34'	65°54'
3	<i>p</i>	(111)	1	Brilliant, good	45°17'	56°26'	45°00'	54°44'

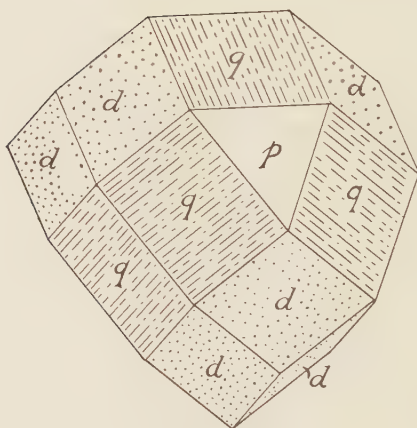
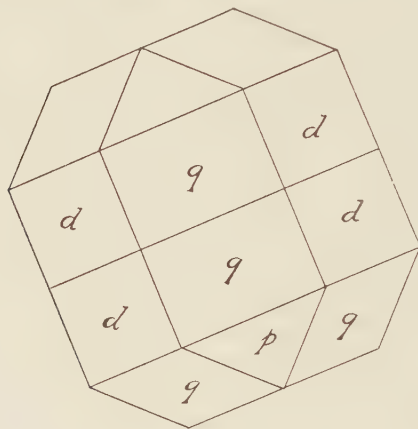


FIG. 1

The tetrahedrite is covered in places with a thin loose shell of fine-grained quartz. The order of deposition in the ore is:

- 1—quartz
- 2—sphalerite
- 3—miargyrite
- 4—quartz
- 5—miargyrite
- 6—tetrahedrite
- 7—quartz

The Flint district in which these specimens were found is not far from the mines in which miargyrite was found in the Silver City District. This is the only region in the United States where the mineral occurs except the Randsburg district in California where, within the past few years, very fine both massive and crystallized miargyrite has been found as the most abundant silver mineral of the ore. The crystallography of this California material is now being studied and will shortly be described by the present writer.

THE IMPORTANCE OF POLLUCITE

ERNEST E. FAIRBANKS, *Denver, Colorado.*

INTRODUCTION

Pollucite, $2\text{Cs}_2\text{O} \cdot 2\text{Al}_2\text{O}_3 \cdot 9\text{SiO}_2 \cdot \text{H}_2\text{O}$, the principal source of caesium, was named in 1846 by Breithaupt from Pollux (the genitive form of which is Pollucis) of heathen mythology. Breithaupt found two minerals constantly associated in the cavities of the Isle of Elba granite, hence the fitness of his choice in applying the names of Castor and Pollux, famous for their fraternal affection and inseparable companionship. Castorite, the associated mineral, is now known as petalite, $\text{Li}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 8\text{SiO}_2$.

The writer prepared a brief paper (which he did not publish) about three years ago on the occurrence of caesium. Since that time he has changed his views regarding the abundance of pollucite. Quarrying pollucite has commenced since that time and the writer visited the quarry from which this mineral was being obtained during the summer of 1927.

COMMERCIAL APPLICATION OF CAESIUM

The application of caesium was for several years practically limited to the use of its compounds as reagents in the rapidly developing field of chemical microscopy. Owing to its habit, possessed in common with rubidium, of forming salts of marked

crystalline structure, it is almost indispensable as a microchemical reagent.

More recently it was discovered that thermionic effects caused by caesium in the radio vacuum tube increases the efficiency of the tube at a much lower consumption of electric current than has been found in other types of tubes.¹ Caesium was and remains a very rare metal, hence a search was made for a substitute occurring in greater abundance. Thorium, which has a smaller electron affinity, also gives pronounced thermionic effects but it is not a satisfactory substitute. It appears as though caesium is the best suited for use in the vacuum tube.

SOURCE OF CAESIUM

The sporadic production of pollucite from true pegmatites was always sufficient to satisfy the small demands for caesium in the past. This remains the only source at present but the demand is greater than the supply. Pollucite contains 34% Cs_2O and is by far the richest caesium mineral ever found.

The quarry in Newry, Maine, located near Andover, operated by the General Electric Company, is, as far as the writer knows, the only one producing pollucite. While it has been found in other quarries in the Maine gem-bearing pegmatites, at present they have no commercial significance. The cavities in the granite of the Isle of Elba have likewise produced a small quantity of this mineral.

Other caesium minerals known are: Caesium beryl or vorobyevite, containing about 3% of caesium; it is a rare mineral found in the Urals, Madagascar, and in the Maine pegmatites.

Rhodizite, $(\text{Rb}_2\text{O}, \text{Cs}_2\text{O}, \text{K}_2\text{O}) \cdot 2\text{Al}_2\text{O}_3 \cdot 3\text{B}_2\text{O}_3$, is a very rare mineral first identified as minute octahedral crystals on pink tourmaline occurring in the vicinity of Ekaterinburg in the Urals and has since been noted in the pegmatites of Madagascar.

Lepidolite, $\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 2(\text{K}, \text{Li})\text{F}$, from some localities is said to contain as high as 3% of rubidium oxide and also a small, variable amount of caesium oxide. Lepidolite occurs in deposits of commercial importance in California and South Dakota. Its chief use, probably, is as a flux in glass-making.

Caesium together with rubidium are reported to have been

¹ See especially; Thermionic effects caused by alkali vapors in vacuum tubes: Irving Langmuir and K. H. Kingdon, *Science*, 57, 58-60 (1923).

recovered from carnallite in the Stassfurt region.² Since rubidium appears to show a marked preference for potassium³ it is probable that the quantity of isomorphous caesium present in carnallite is very small. No figures are available on the actual amount found. Certain mineral waters also carry caesium.

PROBABLE ABUNDANCE OF POLLUCITE

Pollucite resembles quartz very closely. A characteristic specimen of pollucite was presented to several mineralogists and geologists for identification. Every one to whom the specimen was presented appeared certain that the mineral was quartz. While the pegmatites have always been the favorite hunting ground of the gem miner and mineralogist, it is probable that pollucite has been mistaken for quartz on many occasions. The mineralogist on the watch for the many spectacular minerals of a pegmatite might easily overlook the inconspicuous pollucite. The occurrence of the minerals found associated with pollucite, in many widely separated localities, lends support to the idea that pollucite may have been overlooked. Undoubtedly it is a very rare mineral but the writer, at least, feels convinced that it occurs in other pegmatites besides those of the Maine area.

According to Clarke and Washington⁴ the original ratio of rubidium to caesium in the magma yielding pegmatite appears to be approximately $\text{Rb}:\text{Cs}=10:1$. This may explain why the amount of isomorphous rubidium always exceeds the quantity of caesium in lepidolite.

ORIGIN OF POLLUCITE

The process by which caesium becomes concentrated from a magma with the approximate ratio $\text{Rb}:\text{Cs}=10:1$ is suggested by the association of lepidolite with pollucite. It is known that rubidium shows a marked preference for potassium, therefore the suggestion presents itself that potassium-bearing lepidolite has robbed the magma of its rubidium, thus concentrating the caesium.

While none of the suggested formulae for pollucite indicate the presence of potassium it may be present in small quantity according to Clarke and Washington.⁵ Microscopic study indicates

² Dictionary of applied chemistry: Thorpe, N. Y. p. 597, (1912).

³ Clarke and Washington: The composition of the earth's crust, *U. S. G. S. Prof. Paper*, 127, p. 203, (1924).

⁴ *Op. cit.*, p. 25.

⁵ *Op. cit.* p. 80.

the presence of finely disseminated feldspar intermixed with the pollucite. Since oligoclase was determined in this disseminated material it is possible that the potassium content may be accounted for by this mineral known to contain, in some cases, as high as 7% of a potassium feldspar molecule.

It may be possible that lepidolite, which occurs in much greater abundance than pollucite, can account for the excess of rubidium in the ratio but it is equally possible that a physico-chemical process has taken place of which we have no knowledge.

IDENTIFICATION OF POLLUCITE

While pollucite resembles quartz, its luster is slightly different and may be best described as somewhat "oily." Conchoidal fracture is common to both minerals but appears to be more completely developed in pollucite. Pollucite is, of course, more apt to show alteration. The hardness of the two are close (pollucite 6.5, quartz 7). The specific gravities are also fairly close (pollucite 2.90, quartz 2.65) and feldspar may be intimately intermixed affecting the determination.

The slight difference in luster and the fact that pollucite is decomposed by acid are of greatest use in the field.

If a microscope is available the distinction becomes simple. Pollucite is isotropic with a refractive index of 1.525 while quartz is uniaxial (+) with $\epsilon=1.553$ and $\omega=1.544$.

MINERAL ASSOCIATIONS

Pollucite at Newry, Maine, occurs frozen in a pegmatite which has been intruded into what is now a chlorite schist. Lepidolite and colorless caesium beryl appear to be the best indicators of the possible presence of pollucite. A great many minerals have been found in this pegmatite, including the following noted by the writer upon the occasion of his visit to the quarry; tourmaline (black, pink, red, and green), purpurite, lithiophilite, columbite(?), cassiterite, caesium beryl, spodumene and lepidolite.

The above mineral association suggests several localities in the world in which pollucite may occur.

OTHER POSSIBLE SOURCES OF CAESIUM

Among the other possible sources of caesium, lepidolite alone appears to offer any commercial possibilities. If the demand for caesium cannot be satisfied by the production of pollucite, which

is improbable at the present at least, it is possible that lepidolites containing caesium could be worked as a source of lithium salts. The added value as a result of a caesium content undoubtedly would enable lepidolite to compete with amblygonite, the present source of lithia.

If the lepidolite produced by California during 1920 amounting to 10,046 short tons, contained the amount of Cs_2O reported in the mineral at Pala, San Diego, there would have been 30 short tons of caesia involved.⁶ Although the analysis shows, Rb_2O 0.97, and Cs_2O 0.30, some doubt exists with regard to the amount of caesium reported in lepidolites and how representative such analyses are of the lepidolite mass.

CONCLUSION

Mineralogists should be on the watch for pollucite whenever an examination is being made of a granite pegmatite. A ready market exists for the mineral at present and perhaps it occurs in many unsuspected localities.

THE MINES AT THE FALLS OF FRENCH CREEK, CHESTER COUNTY, PENNSYLVANIA

GEORGE VAUX, JR.,¹ *Philadelphia Mineralogical Society.*

The vicinity of Philadelphia has long been known as one which abounds in rare and interesting minerals. One needs only mention such occurrences as the pyromorphite and anglesite of Phoenixville, the brucite from Wood's Chrome Mine, the amethyst, garnet, and titanite of Delaware County, to bring to mind some of the more important and beautiful specimens which have been found here in the past. As early as 1818, Isaac Lea published in the *Journal of the Academy of Natural Sciences of Philadelphia* (volume 1, pp. 462-82) "An account of the minerals at present known to exist in the vicinity of Philadelphia," and the bibliography of the subject has been quite extensive from that time to this.

Leaving out of consideration the enthusiasm which so many collectors exhibit towards specimens found locally, which enthusi-

⁶ Non-Metallic Minerals: Raymond B. Ladoo, New York, p. 306, (1925).

¹ This locality was but an hour's drive by automobile from his home and was frequently visited by Mr. Vaux. This article was completed within a few days of his untimely death on October 24, 1927. (S. G. G.)

asm is not always shared by others, there is no doubt that the list of species of this region contains as great a variety and as much of unusual interest as can be found in any other similar area with but one or two striking exceptions such as Franklin, New Jersey region.

It is of further interest to note that of all of these localities there is hardly a single one which at the present time yields specimens of more than passing importance except the mines at the Falls of French Creek. A brief account of this locality and some of the more interesting finds there is the subject of this paper.

The mineralogical history of the region is not known with any degree of definiteness. In the list of American mineral localities as given in Dana, it does not appear at all in the second edition published in 1844, while in the third edition, published in 1850, we find reference to specimens found both at Knauertown, and at Keim's Iron Mine (near Knauertown). In later editions the Elizabeth Mine is added. Also the name of Crossley's Pits is to be found in some of the earlier literature.

The present mines, which are known as those of the Falls of French Creek, cover much more extensive workings than all of the earlier ones which were incorporated in the later operations. The minerals which were considered worthy of special mention by Dana in the above citations included different varieties of garnet and also pyrite.

The adjacent parts of the counties of Lancaster, Chester and Berks, comprise a rough, broken region known as the Welsh Mountains. The country rock is of Precambrian age including Pickering gneiss with lenses of limestone, and Triassic red shale, containing considerable areas of intrusive masses of diabase, solutions from which have formed contact deposits of magnetite which have replaced lenses of limestone in the gneiss. These mineralized deposits have been large enough to produce paying ore at a number of different points.

The name of the locality, Falls of French Creek, is derived from several rapids in a fair sized stream, caused by the water flowing over dikes of diabase which cross it at that point. The present mines are located about half a mile from the little village of Knauertown and about one-eighth mile east of St. Peters Station at the terminus of a short branch of the Philadelphia and Reading Railway. Two old shafts, known as the Keim or lower mine, and the Elizabeth or upper mine, from their respective positions on

the side of the hill, are included in some of the underground workings. The principal slope now operated was driven in 1918, and has reached a depth of some 1400 feet.

Since that date operations have been conducted with considerable activity, the shipment of ore oftentimes running to over 10,000 tons a month. There has been some reduction in output recently, however, as the ore bodies appear to have been largely exhausted, and it may be, in default of new discoveries, that the time is not far distant when operations will cease altogether, and the mine will be abandoned permanently.

A very considerable number of mineral species have been reported from this locality.² Two papers by the late Samuel L. Penfield, one on "Some curiously developed pyrite crystals from French Creek, (Chester Co.), Pa." in the *Am. J. Sci.*, (3) **37**, 209-212, 1889; and the other on "Chalcopyrite crystals from French Creek Iron Mines, St. Peters, Chester Co., Pa.," in the same journal, **40**, pp. 207-211, 1890, brought to our attention for the first time some very remarkable crystals of these two minerals. Drawings of some of the crystals appear in the sixth edition of Dana's System of Mineralogy, on pages 81 and 85. Several of the crystals studied by Penfield are in the writer's collection, including one which measures 6 cm. in length and 4 cm. in width. Further investigation of these remarkable elongated crystals seems very desirable as likely to contribute additional information on their true character.

The mine has produced many unusual specimens of pyrite. Frequently they form interesting hopper-shaped groups of crystals, usually of cubic habit, built up so that the group may be 5 cm. across. Many of the crystals are modified, chiefly by the diploid, *t* (421). The grouping of the pyrite crystals on a gangue of brilliant octahedral magnetite make a very attractive contrast. The magnetite is usually built up so that the final crystals may measure 2 cm. across. Much of the pyrite has an exceedingly brilliant lustre and a very light color. In an article by Genth in 1890 (*Am. J. Sci.*, (3) **40**, p. 117) is given an analysis showing 1.75% cobalt, which might account for this color. A recent partial analysis was made for the writer by Mr. Earl V. Shannon. The specimen

² A practically complete list of the species identified, with references, can be found in the "Mineralogy of Pennsylvania," by Samuel G. Gordon, published by the Academy of Natural Sciences of Philadelphia, 1922, p. 178.

selected was one of very light color, but Mr. Shannon's results were negative with respect to both nickel and cobalt for this particular specimen.

In addition to the chalcopyrite of unusual habit described by Penfield, there were found at one time large masses of that mineral imbedded in a calcite gangue which, when the calcite was dissolved with acid, left the chalcopyrite in beautiful groups of skeleton crystals, single individuals often measuring several centimeters across. These are almost always iridescent and form very spectacular specimens. The past twenty years, however, have produced nothing of this sort; indeed it has been only occasionally that chalcopyrite crystals have been found in recent years.

Among the minerals of most frequent occurrence in the mine has been the fibrous variety of hornblende, byssolite. It is quite common in more or less matted, acicular crystals, sometimes so compact as to produce leather-like masses as large as one's head. It was in this sort of compact byssolite that the pyrite and chalcopyrite crystals described by Penfield occurred. The most beautiful specimens of byssolite, however, are those seen in the crystals of calcite which give these an attractive green color.

In recent years calcite has been among the most plentiful and beautiful of the specimens found, although the number of really spectacular crystals has been limited. Perhaps the finest is a doubly terminated crystal of scalenohedral habit, measuring 10 x 12 x 21 cm., now in the William S. Vaux Collection of the Academy of Natural Sciences of Philadelphia. Rhombohedral crystals are not uncommon and often attain considerable size: one in the writer's collection measures approximately 30 cm. across. Many beautiful negative rhombohedra have been found, with the rhombohedral faces deeply striated horizontally. As usual, the smallest crystals are those most highly modified. A description of a number of new forms shown by them, as well as some of the more general characteristics of the calcite of this locality, will be published shortly.³ Many years ago also specimens of brownish-yellow rhombohedra of calcite were found.

The mineral, however, which has been the most beautiful of any recently secured, has been apophyllite. Thirty or forty years ago specimens were found which consisted of massive coatings on the

³ Paper in preparation by Samuel G. Gordon.

walls of crevices in diabase. More recently, it has become more plentiful. In some parts of the mine it occurs as large, solid masses measured in terms of meters, although the extent of these has not been fully investigated. Three or four years ago a considerable quantity of apophyllite was found with a platy habit, and brilliant white color. Later, more prismatic crystals were found, sometimes yellowish or flesh-colored. Eighteen months ago a small number of nearly opaque crystals of a very beautiful olive-green color, caused by the inclusion of byssolite, were found. Most of the crystals were completely developed on all sides. These measure up to 4 cm. in diameter, and at a glance resemble dodecahedra of green garnet, owing to the almost equal development of base and pyramid, and suppression of the prism faces. The base is characteristically pearly, and built up of smaller crystals to about the same level, while the pyramid faces are scattered over with very minute crystals of apophyllite which show no crystallographic relationship to the larger crystals.

In view of the large amount of apophyllite discovered, and its proximity to the ore bodies, it would be interesting to discuss how far fluorine might have been the mineralizing agent which was the important factor in the formation of the ore bodies.

NOTES AND NEWS

THE STATUS OF KEELEYITE

EDGAR T. WHERRY, *Washington, D. C.*

One of the most serious defects in modern determinative tables based on mineragraphic methods is the almost complete lack of information as to the chemical composition of the material on which observations are made. Fortunately many workers now realize this, and creditable efforts have been made from time to time to determine mineragraphic reactions on analyzed specimens. It was something of a surprise, however, to read in a recent number of this magazine,¹ a paper on a sulfosalt mineral in which the importance of knowledge as to composition of comparison material was ignored, and a conclusion reached which is completely at variance with the facts.

Keeleyite was originally described by S. G. Gordon² as $2\text{PbS} \cdot 3\text{Sb}_2\text{S}_3$ on the basis of an erroneous recalculation of a commercial analysis on an impure specimen. As a formula derived in such a manner would be to say the least unconvincing, and as the properties listed were identical with those of zinkenite (which is recorded as occurring at the locality), in tabulating the minerals described during 1922

¹ *Am. Mineral.*, 12, 405, Nov., 1927.

² *Proc. Acad. Nat. Sci. Phila.*, 74, 101, 1922.

keelelyte was placed in quotation marks by the writer³ to show it to be discredited, the reason being given that it was a variety of zinkenite.

Shannon and Short now conclude that it "can be accorded full species rank." They supply a good analysis on microscopically homogeneous material, which leads to the formula $\text{PbS} \cdot \text{Sb}_2\text{S}_3$ (with minor amounts of replacement) identical with that universally adopted for zinkenite.⁴ Nevertheless they consider the two minerals distinct because of the presence in the keelelyte of 3.26% of metals other than lead, notably including 1.24% of zinc, and because of certain mineragraphic differences.

Henglein⁵ cites ten analyses of zinkenite, and in the eight of these in which metals other than lead were determined the amounts are: 0.42, 0.76, 0.80, 1.57, 1.83, 2.21, 3.10, and 4.23. Accordingly keelelyte is identical with zinkenite with respect to the presence of a few percent of minor constituents. Although zinc was not reported as such in any of these analyses, it was probably not looked for in any except perhaps Hillebrand's, but was weighed as iron, copper, or silver, one or more of which are present throughout.

The analyzed keelelyte differed mineragraphically on four out of eleven counts from another sulfosalt which Shannon and Short examined. But they gave no data as to the identity of this other sulfosalt except to say that it was labelled zinkenite. There is no information as to whether it had the ratio $\text{PbS} \cdot \text{Sb}_2\text{S}_3$, nor whether it contained zinc replacing the lead.

The claim of keelelyte to be a distinct species accordingly rests on the presence of a little more than 1 per cent of zinc—far too little to be represented in the formula—and a few mineragraphic differences, which may well be due to its zinc content, from a specimen of unknown composition which may have represented zinkenite, and which may or may not have had the same ratio. I therefore regret that I can not agree with the writers in question. They have shown that keelelyte has the zinkenite formula and that it contains enough replacement of the lead to account for minor differences in properties. Instead of establishing its specific rank, it seems that they have thus demonstrated that keelelyte is, as previously suggested, only an impure variety of zinkenite.

M. A. Lacroix, professor of mineralogy at the University of Paris, has been made a foreign member of the Stockholm Academy of Sciences.

J. E. Morrison, secretary of the San Diego, California, Chamber of Mines, has been appointed honorary curator of minerals at the Natural History Museum, San Diego.

At the University of Texas, the Bureau of Economic Geology has moved into new and better quarters. A two story fire proof building has been provided for laboratory and museum space with additional space in other buildings for offices and general storage. A mineralogical laboratory will be installed in the Bureau's new building and will be equipped through a special appropriation recently made by the Board of Regents.

³ *Am. Mineral.*, 9, 175, 1924.

⁴ Dana, *System*, 112; Groth & Mieleitner, *Min. Tab.*, 24, 1921.

⁵ Doelter's *Handbuch Mineralchem.* 4 (3) 449, 1925.

Professor P. von Groth, for many years professor of Mineralogy at the University of Munich, Germany, died Dec. 2, 1927, in his eighty-fifth year. A biographical sketch of his life and contributions to mineralogical science will appear in a later number of the JOURNAL.

REVIEWS

REVIEW OF AN INVESTIGATION OF THE RATE OF GROWTH OF CRYSTALS IN DIFFERENT DIRECTIONS

An excellent piece of research on the growth of crystals, by Dr. Marie Bentioglio, working under the direction of Dr. Barker and Professor Bowman at Oxford University, has just been published in the *Proceedings of the Royal Society*,¹ and as this journal is probably not accessible to many of the readers of the *American Mineralogist*, this review has been prepared to call the attention of crystallographers to the significant results obtained.

While the experimental methods employed were similar to those of Wulff, many important improvements were introduced. The crystal under study was held at the center of a horizontally-placed flask filled with 500 cc. of solution, the zone of faces to be measured being horizontal, and the flask being slowly rotated on the axis of this zone. To hold the crystal a hole was drilled into it, and a long fine pin fixed into this with wax, the pin being then clamped to a rod attached to the stopper of the flask. To measure the amount of growth, the rod was detached and mounted on a tripod so that it could be slid along on a glass plate, under a microscope with magnification of 75 diameters, readings being obtained by means of a milled head, graduated in 0.01 mm.

Crystal growth was effected by slow cooling of the solution, the best initial temperatures being found by trial to be: sodium chlorate, 35–37°; K-alum and double sulfates of Mg or Fe with K or (NH₄), 30–34°; K and (NH₄) tartrates, 40°C. A fall in temperature of 10–12° in 4–5 hours was attained by wrapping the flask in cotton, and proved adequate. The results are tabulated in detail and illustrated by crystal drawings, and lead to the following conclusions: (a) On crystals bounded by a single form, all the faces grow at the same rate, irrespective of their original sizes. Hence a distorted crystal may tend toward, but never quite attain, ideal development with the faces all equal in size. (b) On crystals bounded by a combination of forms, unlike faces grow at different rates, but like faces grow at the same rate. An exception to the latter relation may occur when the faces lie adjacent to a larger face of another, fast-growing form, for the latter may impoverish the solution in its neighborhood, and slow up the growth of faces surrounding it. (c) On crystals lacking a center of symmetry, the growth-rates of parallel faces may be widely different. (d) In an isomorphous series, the order of increasing rates of growth of different forms is not the same for different members.

While these results are interesting in throwing light on the manner of development of crystal habit, their greatest value lies in their bearing on the theory of the relation between crystal structure and form. The frequently accepted view, favored by Wulff and carried to an extreme by Fedorov, is that the rate of growth of a given form is directly related to its reticular density, *i.e.*, the packing of

¹ *Proc. Royal Soc. (London)* A, 115, No. A 870, 59–87, June 1, 1927.

leptons (atoms, ions, or molecules) in the layers parallel to the faces of this form. The closer the packing, it is supposed, the slower the growth-rate of a form; then, since slow-growing faces are the ones which persist the longest and become the largest as the crystal grows, the dominant faces on a given crystal are taken to be those of greatest reticular density.

The fallacy of this view is clearly shown by the results reported here: (a) In the isomorphous series of double salts, the reticular densities of different forms must be relatively the same from one member to another. Yet it is found that the relative growth-rates of different forms vary widely among the different salts, the form τ (201) being actually the fastest-growing form on one substance and the slowest-growing on another in the same series. (b) Even more significant is the finding that the forms situated at opposite ends of a polar axis, which must necessarily possess the same reticular density, nevertheless grow at markedly dissimilar rates. Crystal growth and crystal habit are, accordingly, not merely a matter of the geometrical relations involved in the packing of leptons; they express the result of oriented attractions on the part of the leptons lying at the surface of the crystal.

E.T.W.

PROCEEDINGS OF SOCIETIES

PHILADELPHIA MINERALOGICAL SOCIETY

Academy of Natural Sciences of Philadelphia, November 3, 1927.

A stated meeting of the Philadelphia Mineralogical Society was held on the above date with the Vice-president, Mr. Clay, presiding. Twenty-five members and seven visitors were present.

Mr. Charles R. Toothaker of the Commercial Museum was elected to membership.

Mr. Clay spoke of the recent death of the Society's President, George Vaux, Jr., and the loss to the Society of his friendship and leadership. A resolution expressing the sympathy of the Society to his family was unanimously adopted.

The Society then heard a very interesting address by Mr. Charles R. Toothaker who spoke on: "RAMBLES THROUGH BRAZIL: DIAMONDS, GEMS, IRON AND MANGANESE." The speaker described his visits to the gem regions of Brazil, the manganese mines at Lafayette and the iron deposits at Burnier. Of special interest was his account of the diamond diggings along the Jequitinhonha river in Minas Geraes, the topaz at Ouro Preto, the quartz from Goyaz and the agate localities along the Uruguay border. The address was profusely illustrated with colored lantern slides and by means of specimens of Brazilian gems and other minerals.

Mr. Biernbaum described a trip to Paterson, N. J., Mr. Oldach spoke of trips to Franklin, N. J. and French Creek, Pa. and Mr. Cienkowski of a trip to Moores and Stockton, N. J.

F. A. CAJORI, *Secretary*

NEW MINERAL NAMES

L. L. FERMOR: Composition of some Indian garnets. *Records Geol. Surv. India*, 59, 191-207 (1926).

Skiagite

NAME: From the locality, Glen *Skiag*, Scotland.

CHEMICAL PROPERTIES: The ferrous-ferric garnet molecule, $3\text{FeO} \cdot \text{Fe}_2\text{O}_3 \cdot 3\text{SiO}_2$ is present in the garnets of Nautan, Barampur (3.45%), Garbham, Vizagapatam (5.40%) and Katkamsandi (19.50%). Also in the garnet from Glen Skiag, Scotland (Dana, spessartite No. 14).

Blythite

NAME: In honor of Mr. T. R. *Blythe*, late assistant curator to the Geological Survey of India.

CHEMICAL PROPERTIES: Contains the manganous-manganic garnet molecule, $3\text{MnO} \cdot \text{Mn}_2\text{O}_3 \cdot 3\text{SiO}_2$. Found in the Chargon, Nagpur garnet (34.72%).

Calderite

NAME: (The garnet rock from Hazáribágh has been called *calderite*. Undoubtedly the mineral name is taken from this rock name).

CHEMICAL PROPERTIES: Contains the manganous-ferric garnet molecule, $3\text{MnO} \cdot \text{Fe}_2\text{O}_3 \cdot 3\text{SiO}_2$. Found in the Chargon, Nagpur (12.81%), Garbham, Vizagapatam (17.02%) and Katkamsandi, Hazáribágh (68.56%) garnets.

Ferro-Calderite

The Katkamsandi, Hazáribágh garnet is called *ferro-calderite*. It contains 25.34% skiagite and 68.56% calderite.

Magnesioblythite

The Chargon, Nagpur garnet is called *magnesioblythite*. It contains 5.40% MgO. Color orange red to orange.

(Other new terms used are *Mangan-almandite*, *Ferro-spessartite*, *Calc-spessartite* and *Mangan-grandite*).

Metamilarite

FRIEDRICH RINNE: Milarite und metamilarite. *Centr. Min.*, 1-14, 1927.

An artificially dehydrated milarite.

W. F. FOSHAG

REDEFINITION OF SPECIES**Phosphoferrite**

ORIGINAL DESCRIPTION: H. LAUBMANN AND H. STEINMETZ. *Z. Kryst.*, 55, 569-570, 1920. (See. *Am. Mineralogist* 6, 67, 1921).

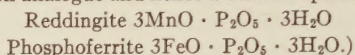
NEW DATA: H. Steinmetz: *Z. Kryst.*, 64, 407-412 (1926).

CHEMICAL PROPERTIES: A hydrous phosphate of iron and manganese, $3(\text{Fe}, \text{Mn})\text{O} \cdot \text{P}_2\text{O}_5 \cdot 3\text{H}_2\text{O}$. New analysis: FeO 37.52, MnO 13.63, CaO 1.20, P_2O_5 34.39, H_2O 13.31. Sum 100.06.

CRYSTALLOGRAPHIC PROPERTIES: Orthorhombic bipyramidal. $a:b:c=0.8629:1:0.9418$. Several habits are present but usually the crystals are tabular parallel to b . Rarely pyramidal. Nineteen forms were noted. Cleavage b , good.

OPTICAL AND PHYSICAL PROPERTIES: Color green. Biaxial positive. Plane of the optic axes (010), $B_x = c$. Sp. Gr. 2.96-3.10.

DISCUSSION: Steinmetz considers phosphoferrite as an iron rich reddingite. (Inasmuch as iron greatly predominates over manganese phosphoferrite can well be considered as its iron analogue and hence a distinct species.)



W. F. F.

Phosphophyllite

ORIGINAL DESCRIPTION: H. LAUBMANN AND H. STEINMETZ: *Z. Kryst.*, **55**, 523, 1920 (See, *Am. Mineralogist*, **6**, 65, 1921).

NEW DATA: H. Steinmetz: *Z. Kryst.*, **64**, 405-407 (1926).

CHEMICAL PROPERTIES: A hydrous phosphate of zinc, iron and manganese, $3(\text{Zn, Fe, Mn})\text{O} \cdot \text{P}_2\text{O}_5 \cdot 4\text{H}_2\text{O}$. New analysis: FeO 12.24, MnO 4.96, ZnO 34.26, P_2O_5 32.51, H_2O 16.52. Sum 100.49.

OPTICAL PROPERTIES: $\alpha = 1.595$, $\beta = 1.606$, $\gamma = 1.617$.

OCCURRENCE: Found as a secondary mineral derived from primary iron-manganese phosphates and sphalerite.

DISCUSSION: The original analysis by Spengel is erroneous. The mineral is essentially a zinc phosphate similar to hopeite but differing from it in being monoclinic instead of orthorhombic.

W. F. F.

DISCREDITED SPECIES

Carrollite

EARL V. SHANNON: The identity of carrollite with linnaeite. *Am. Jour. Sci.*, **11**, 489-93 (1926).

Samples of carrollite from all available sources proved upon metallographic examination and chemical analysis to be either linnaeite without copper or a mixture of linnaeite and secondary chalcocite.

W. F. F.

Prolectite

PER GEIJER: Notes on the crystals described as prolectite. *Geol. För. Förh. Stockholm*, (1926), pp. 86-89.

A re-examination of Sjögren's original specimens showed $\alpha_{\text{Na}} = 1.623$, $\beta_{\text{Na}} = 1.637$. These and the properties given by Sjögren are very near the chondrodite associated with the mineral. Further the composition assigned to prolectite (no analysis was made) is the same as that determined by Geijer for the new mineral norbergite which, however, has different optical properties. Prolectite is apparently only chondrodite.

W. F. F.

Arsenolamprite

H. JUNG: Über arsen und phosphor. (Concerning Arsenic and Phosphorus). *Centr. Min. Geol.*, No. 4, (1926), p. 111.

An X-ray examination of columnar, platy arsenolamprite from Copiapo, Chile, and Marienberg gave many lines identical with those of rhombohedral arsenic so that arsenolamprite probably represents only an impure arsenic.

W. F. F.